Study on eight-pass dual-frequency laser interferometer with nanometer precision

Haijun Gao (高海军), Zhaogu Cheng (程兆谷), Zhigao Ning (宁志高),
Pinjing Cui (崔品静), and Huijie Huang (黄惠杰)

Precise Optoelectronic Measure and Control R&D Center, Shanghai Institute of
Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

Received January 25, 2005

A new dual-frequency laser displacement measurement interferometer with nanometer precision has been developed. An eight-pass optical subdivision technology is proposed to improve resolution based on commercial interferometers. A static positioning error measuring method has been used to examine the precision and repeatability of the laser interferometer. An optical resolution of 1.24 nm and an accuracy of nanometer scale have been achieved.

OCIS codes: 120.0120, 120.3180, 250.0250.

Dual-frequency laser interferometer has the advantages of wide measuring scope, high speed, and high precision. It is widely applied to the precision and super-precision length measuring, especially used in locating of wafer stage in high precision step and scan lithography, which is un-substitutable. Though the technology of dual-frequency laser interferometer was developed and achieved to a relatively mature level, it is still focused because of the exigent requirements in the advanced manufacturing area and the fast growing nanometer technology[1−6].

Here we briefly introduce the basic formulas and principle of the measurement using a dual-frequency laser interferometer[7]. The dual-frequency He-Ne laser emits a coherent light beam composed of two slightly different optical frequencies, f_1 and f_2, of opposite circular polarization. In a typical installation, the beam is sent through a polarizing beam splitter (PBS). f_1 goes to a corner retroreflector on the object whose position is being measured and f_2 goes to a corner reflector fixed with respect to the beam splitter. The returned frequency from the object corner retroreflector is $(f_1 \pm \Delta f)$. It is recombined with f_2 and sent to a receiver module, generating a new difference frequency, $(f_1 - f_2 \pm \Delta f)$. This is mixed with the original $f_1 - f_2$ reference to produce an output which is then simply $\pm\Delta f$, that is

$$\Delta f = f_1 2V/c, \tag{1}$$

where V is the velocity of the object, c is the velocity of light.

If the velocity of the object is $\mathrm{d}L/\mathrm{d}t$, distance $\mathrm{d}L = V\mathrm{d}t$, $\lambda = c/f_1$, we can obtain

$$L = \int_0^t V\mathrm{d}t = \int_0^t (\lambda\Delta f/2)\mathrm{d}t. \tag{2}$$

Because $\int_0^t \Delta f \mathrm{d}t$ is the integral fringe N within period t, Eq. (2) can be written as

$$L = \frac{\lambda}{2}N. \tag{3}$$

The absolute accuracy of laser interferometers employed in displacement metrology is limited by two dominant factors: uncertainties in the source vacuum wavelength and the refractive index of the ambient air. Recently, the vacuum wavelength stability of a commercial interferometer could be ±0.002 ppm typically within one hour, which can fulfil and ensure the precision and stability by calibrating on time. The refractive index of air is a well-known function of atmospheric pressure, air temperature, water vapor partial pressure or relative humidity, and carbon dioxide concentration by volume. Even tiny changes of these parameters can affect the refractive index[8].

In order to obtain high accuracy measurements, high resolution of interferometer is necessary. There are two useful methods for this purpose, one is called electronic fringe subdivision which subdivides electronic signal of the interferometer into, for example, 4, 8, 16, 32, 64, and 128 subdivisions and so forth; the other is called optical subdivision which multiples optical path difference (OPD). The optical subdivision has the advantage of changing displacement information to multiple optical path difference, which could enhance the ability of disturb-resisting and measuring precision of the dual-frequency laser interferometer.

In this study, the resolution and the stability of a commercial interferometer, with the principle diagram shown in Fig. 1, are improved only by adding a plane mirror and three corner-cubes before the input gate of the detector of the device and by changing the switch to the mode of the same gate of input and output of the beams, as

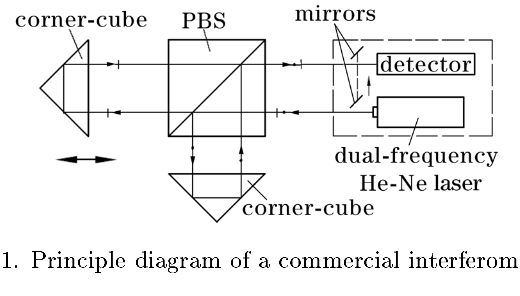

Fig. 1. Principle diagram of a commercial interferometer.

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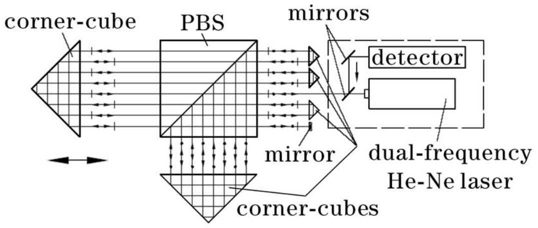

Fig. 2. Principle diagram of the eight-pass laser interferometer.

illustrated in Fig. 2. An optical subdivision with the resolution improved by eight times was obtained, resulting in a four-fold enhanced measurement resolution by reducing the measurement velocity.

The vacuum wavelength (λ) of dual-frequency He-Ne laser is 632.991354 nm, the original resolution of the above commercial interferometer is 10 nm, i.e. $\lambda/64$ subdivision[9]. In our study, it could achieve $\lambda/512$ after further optical subdivision, i.e., 1.24 nm.

A larger number of optical passes gives higher optical resolution and therefore eases the burden of electronic fringe subdivision. A larger number of optical passes is particularly attractive in nanometer level applications.

There are various factors that may affect the values of mixing errors in an eight-pass configuration. It is found that optical mixing errors in the eight-pass interferometer are sensitive to the misalignment between the laser beam polarization orientation and the beam splitter but less sensitive to other misorientations and imperfections of optical components. A complete cycle of nonlinear error variation for this particular configuration requires four interference fringe counts, rather than one.

In order to carry out the true measuring precision of the dual-frequency laser interferometer, higher stability of the target is more important compared with the performances of the interferometer, such as wafer stage with the precision of nanometer level in lithography. Measurement environment also has critical requirement as the running environment of the wafer stage. Meanwhile a higher precision instrument is a must in result analysis. It is very difficult to meet all the above requirements in a common laboratory.

The four core parts of the instrument, laser source, PBS, reference and measuring corner-cube retroreflectors (CCRs), are shown in Fig. 2. Experimental results show that the relative stability of them is very important. If the PBS, the reference and measuring CCRs combine together as one part, environment error and deadpath distance error can be decreased to zero under such limiting state. Thus the stability of the instrument can be increased by decreasing the errors, long time (tens of minutes) stability can be reached easily. The precision is better than 1 nm, as can be seen from the measurement results shown in Fig. 3.

One static positioning error measuring method can be used to measure the accuracy, linearity, and repeatability of the instrument itself[8]. The laser interferometer system in this way has recently been used to measure the static positioning errors to examine its precision and repeatability. The target to be measured is set up on a linear stage with high stability and rigidity, which is a dovetail slide and fixed on a large and stable base. The positioning errors of the target were measured over a total range of 500 mm. The moveable measuring CCR was attached to the measurement target, while the PBS with the reference CCR and associated optics were fixed to the same stable base. Put the reference CCR, PBS, and the measuring CCR in a box is one way to decrease environment errors caused by air floating etc.. The errors were measured at each 50-mm interval over the full range, with each point being sampled for 5 times in two seconds. During each two seconds of the measurement period, eight measurements were performed. The errors handling is according to ISO 230-2 1997 2.0σ. The positioning error is defined as the half value of the difference between the maximum and minimum values of the eight measured data. The results of these measurements are shown in Fig. 4. After getting the relative precision of the instrument, we could get the absolute measuring precision through the calibration process.

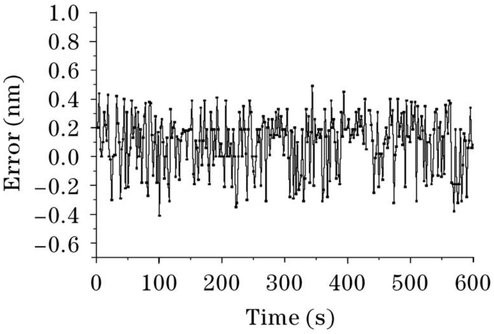

Fig. 3. Measurement results of stability of the interferometer in 10 minutes (sampling at 2-s intervals).

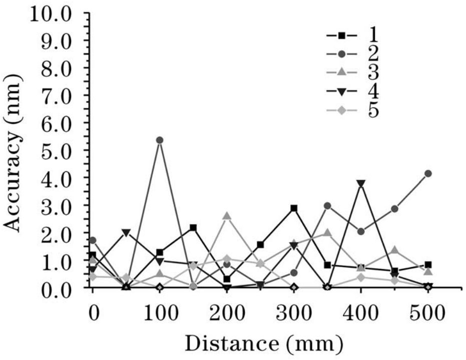

Fig. 4. The measurement results of the static positioning errors with each point sampled for 5 times.

In conclusion, by means of OPD multiple technology and modification of electronic processing of a commercial interferometer, the measurement results of the static positioning errors are within 5 nm for 55 samples during 20-s period. During such a short period, the fluctuation of environmental conditions was reduced to an acceptable level even in a laboratory without clean room equipment. The accuracy, linearity, and repeatability of nanometer-scale measurements can be obtained for displacements larger than 500 mm. The measurements of moving targets with velocities higher than hundreds of millimeter per second have also been performed. However, in this case, we need another interferometer with higher accuracy to calibrate its resolution.

This work was supported by the Optical Science & Technology Project of Shanghai Municipal Science and Technology Commission under Grant No. 022261052. H. Gao's e-mail address is gaohj@siom.ac.cn.

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